DC House Modeling and System Design

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June 2011

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Acknowledgements

I would like to acknowledge the power instructors at California Polytechnic State University- San Luis Obispo, my family for giving me motivation to succeed, and my best friends for being there for me through all this research. I would like to exclusively acknowledge Dr. Taufik for encouraging his students to reach out to their neighbors, and to never have a limit to the possibilities that we can attain.

Abstract

This project entails the study and design of DC power distribution for the DC House Project. Wire size, common high efficient loads, maximum power input, and different distribution system implementation (ring or radial) play a major role when designing an efficient, low-voltage distribution system. Efficiency is determined based on which main bus voltage powers all the loads with minimal power loss. Power efficiency is heavily dependent in DC-DC converter efficiencies due to the power loss in converting the voltage from high to low, or vice versa. Selection of the wire size plays a major role in power losses. There are trade-off with every design, the analysis of four different efficiency test will determine which main bus voltage will be the best fit for the DC Power House considering realistic loads.

I. Introduction

Renewable energy resources have the potential to provide long-lasting solutions to the problems faced by a nation [1]. From greenhouse gas emissions to poverty; renewable energy resources can foster an economy and help the environment. Renewable energies is widely perceived as a promising technology for electricity generation in remote locations in developing countries. The simple gift of light to a third-world country is the start of a self-fulfilling economy. The application of DC distribution of electrical power is proven to be an effective method of power delivery. The losses due to the reactive power component are neglected in DC distribution increasing efficiency by reducing losses due to an increase in current magnitude for an equal amount of transferred power [2]. Internally many appliances operate using DC voltages allowing DC distribution to be fully incorporated to sustain power for a home in a third-world country [2]. Renewable Energy typically produces DC power; making it a viable source for the DC power house. The best solution of rural electrification is through distributed power (small wind farm, solar, etc) versus centralized power (nuclear, large wind farms, etc). Power is not easily accessible in some rural areas in third world countries making distributed power the viable solution.

II. Background

DC House Project Overview

The DC House is designed to power a home in a village where there is no access to electricity. DC house allows unfortunate villages to improve their style of living. The DC power house will include various types of generation, including: photo-voltaic, wind power, hydro-power, and human-powered as show in Figure 2-1. This autonomous DC house will be grid-independent also caleed stand-alone system. The main components with approximate energy losses for the stand-alone DC House are listed in Table 2-1.

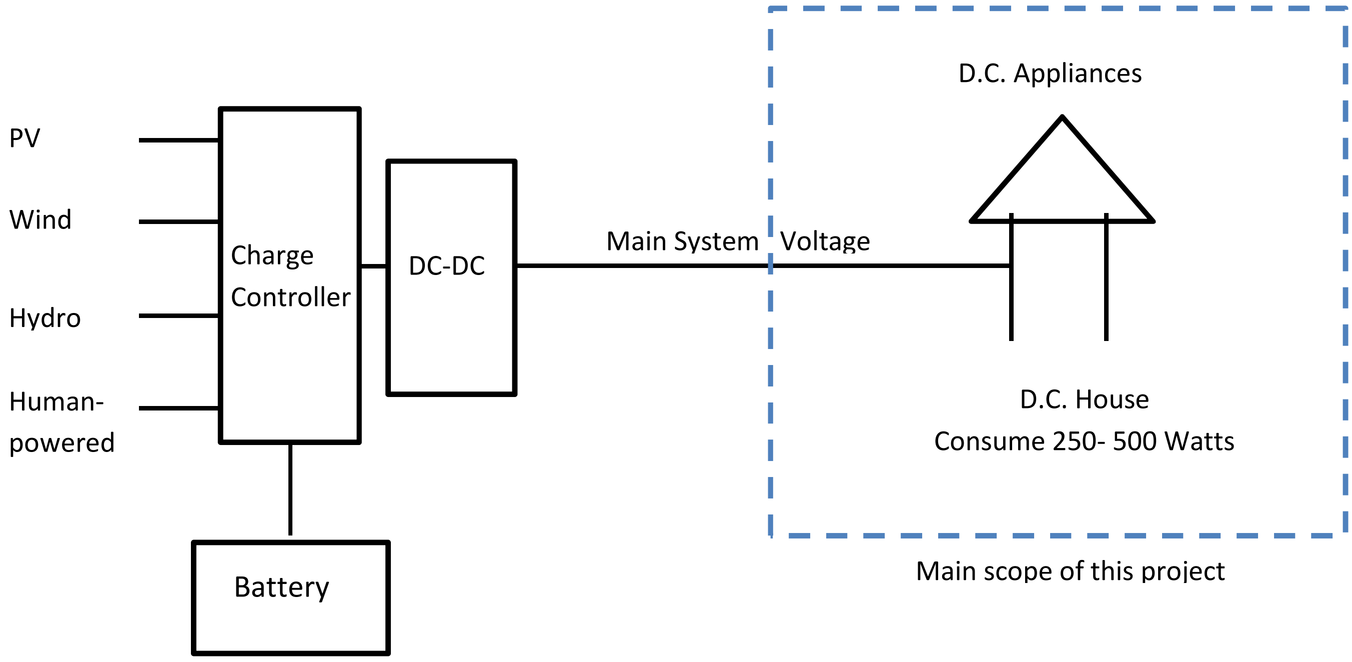


Figure 2-1: DC Power House Overview

	Generation	Charge controller	Battery	DC low-Voltage Grid	Household appliances
Function	Conversion of solar, wind, hydro energy to electrical energy	Control of energy flow to and from battery	Storage of electrical en	DC power transmission from supply to the user	Conversion of DC power to heat, rotation, noise, light
(Avg.) Losses	80%	20%	20%	Depends on main bus voltage	15%

Table 2-1: Components of a stand-alone DC low-voltage house

New developments in the area of power electronics have made a huge impact in DC power transmission. The main advantages of DC power transmission are: reduction of energy losses, simple integration of renewable energy resources such as PV, simple coupling with storage systems, and higher power densities. Many authors have investigated the feasibility of the adoption of direct current in low and medium voltage systems. It has been shown that if the losses in DC-DC converters are considerably reduced, the total system losses are decreased significantly when DC is used. The efficiency of the DC house is interdependent on the efficiency of the DC-DC converters. DC-DC converters typically have an efficiency of 77%-95% depending on DC-DC converter manufactures [2]

Power Transfer in DC Network

For the DC circuit shown in Figure 2-2 current, voltages, and power loss are calculated. It can be shown mathematically that power and voltage losses increase with rising load power as well as with decreasing system voltage. Derivation is shown in Table 2-2. Table 2-2 shows that the current increases if the same power is transported at a lower voltage. Due to this current increase, the voltage and power losses in the conductors will increase; illustrating that the voltage losses and power losses will be considerably larger in the very low voltage system. In

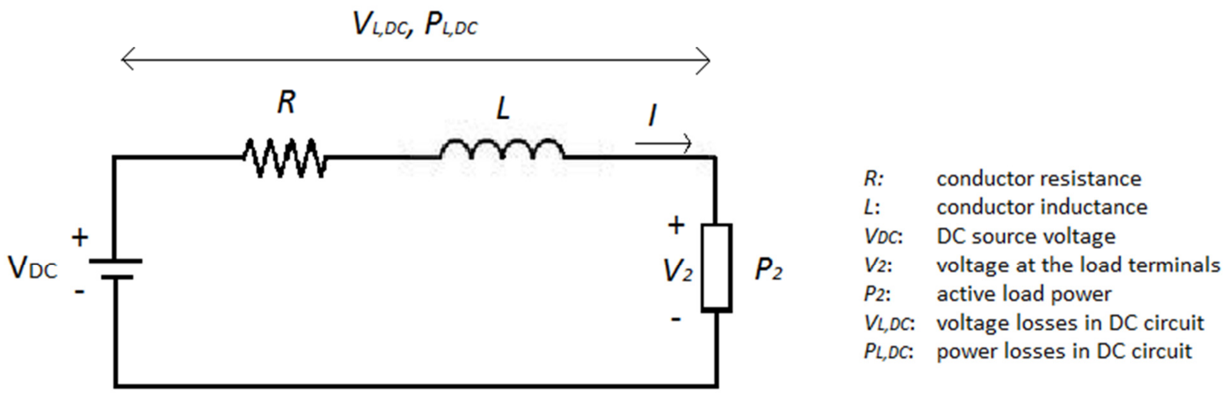


Figure 2-2: DC Network

addition to the problem of voltage losses, another problem in networks will arise in DC low-voltage circuits due to the limitation of short circuit currents [1].

Table 2-2: Power Loss Derivation for DC Circuit

DC Circuit Power Loss
$P_2 = V_2 * I_{DC} \rightarrow I_{DC} = \frac{P_2}{V_2}$ $V_{L,DC} = V_{DC} - V_2 = I_{DC} * R = \frac{P_2}{V_2} * R$ $P_{L,DC} = P_{DC} - P_2 = (V_{DC} * I_{DC}) - (V_2 * I_{DC}) = I_{DC}^2 * R = \left(\frac{P_2}{V_2}\right)^2 * R$ $P_{L,DC} = \left(\frac{P_2}{V_2}\right)^2 * R$

III. Requirements

Objective

The objective is to assess the energy efficiency of a small-scale DC distribution system and to provide a general framework for the implementation thereof. The main goal is to determine the main bus system voltage that will generate the highest system efficiency when accounting for: wire size, different loads, maximum of 500 W power input, and different distribution system implementation (ring or radial).

Targets

To cover all aspects related to the goal of the project the following points will be addressed:

1. Information on average electricity consumption in a developing country. The electricity consumption must be as low as possible.
2. To answer the question of efficiency in correspondence with different loads, DC household appliances should be studied. An inventory is required of all available DC appliances that may be needed in a rural environment
3. The power demand in houses from household appliances must be approximated in advance in order to design a low-voltage DC supply system.
4. Using the approximated data of the power demand, a low-voltage DC distribution system must be designed that is able to supply all DC appliances with sufficient quality. The distribution system must be designed to have minimal energy losses.
5. The DC low-voltage grid must fulfill some technical and safety requirements of the NEC codes for low-voltage installations.

Organization of Project

The timeline of the project is derived from the targets set. Figure 3-1 is an overview of the organization of the project. Figure 3-2 gives a schematic view of the overall project using Gantt chart structure.

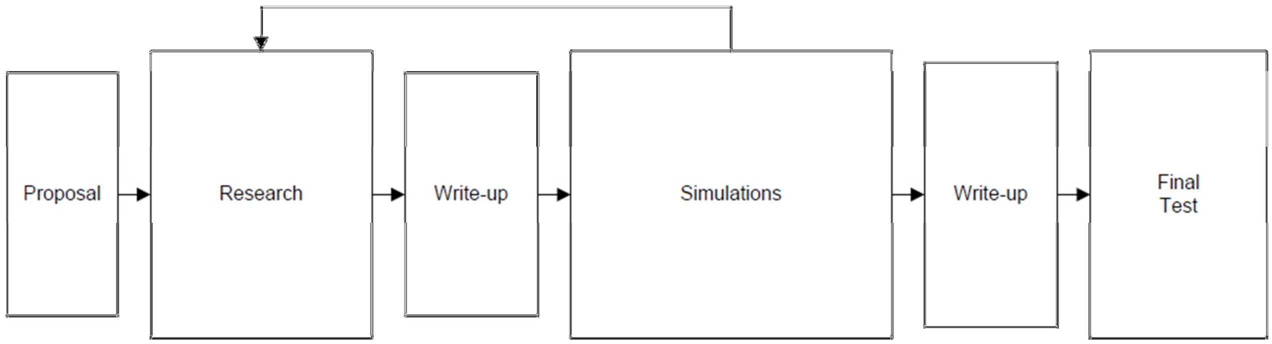


Figure 3-1: Overall outline organization of project

WBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining
1	**Reseach**	JEC	1/26/11	3/11/11	44	28%	0	12	32
1.1	Types of DC Loads		1/26/11	2/14/11	19	98%	0	18	1
1.2	Model Loads		2/02/11	3/11/11	37	55%	0	20	17
1.3	Power Distribution		2/09/11	3/11/11	30	7%	0	2	28
1.4	Primary Bus Voltage		2/16/11	3/11/11	23	0%	0	0	23
1.5	Industry Interviews		2/02/11	3/11/11	37	0%	0	0	37
2	**Model Loads**	JEC	3/28/11	5/01/11	34	0%	0	0	34
3	**Power Distribution**	JEC	4/15/11	5/08/11	23	0%	0	0	23
4	**Efficiency**	JEC	5/01/11	5/17/11	16	0%	0	0	16
5	**Test Software**	JEC	4/15/11	5/20/11	36	0%	0	0	36
5.1	Sub Task level 2		4/15/11	5/20/11	35	0%	26	0	35
6	**Senior Project First Draft**	JEC	1/26/11	5/20/11	114	0%	83	0	114
6.1	Introduction		1/26/11	3/11/11	44	0%	33	0	44
6.2	Background		2/02/11	3/11/11	37	0%	28	0	37
6.3	Requirements		2/09/11	3/11/11	30	0%	23	0	30
6.4	Design		3/28/11	5/20/11	53	0%	40	0	53
6.5	Test Plan		4/04/11	5/20/11	46	0%	35	0	46
6.6	Development and Construction		4/11/11	5/20/11	39	0%	30	0	39
6.7	Integration and Test Results		4/18/11	5/20/11	32	0%	25	0	32
6.8	Conclusion		5/01/11	5/20/11	19	0%	15	0	19
6.9	Blibiography		3/28/11	5/20/11	53	5%	40	2	51

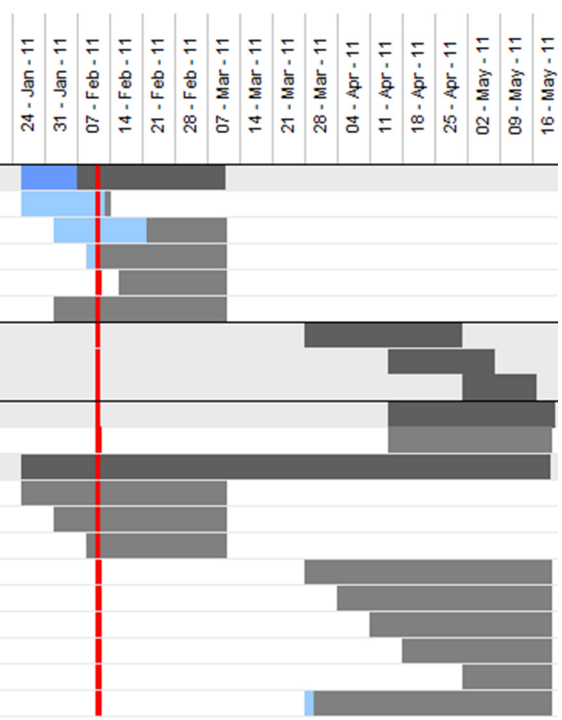


Figure 3-2: Timeline of project

Criteria

The following criteria will be used to determine the efficiency of the system based on bus voltage: the technical efficiency of the DC-low voltage house and the economic aspects. For a full assessment of the DC House social and environmental aspects should be considered [1].The technical efficiency can be analyzed in different ways. The first is to take into account current technologies and circumstances. Second, is to assume that the development of power electronics will make power conversion very efficient and therefor increasing efficiency throughout the DC House. Also, the power consumption should be as low as possible (<500W); only super-efficient loads are to be installed in the DC House. The DC House voltage will range from 12V to 78V. The boundary conditions will have a strong effect on the outcome of efficiency. Efficiency increases dramatically as the voltage increases. The voltage in this case is limited to 78V. It has been proven that a voltage of 320V is very efficient, but this voltage will not be considered in this project [1].

IV. Design: The DC Distribution System

This section will consider the design of the DC low-voltage Power House distribution system. The design must fulfill the following requirements:

1. DC electrical energy must be transferred from the source to the user with minimal energy losses.
2. The DC electrical installation must be safe for the user; referencing NEC guidelines.
3. The voltage quality of the supplied energy must be high enough to guarantee proper functioning of the household appliances connected to the DC grid.
4. The economics factor will be taken into consideration when designing the DC distribution system.
5. DC low-voltage network must be easy to install and maintain.

The following sub-headings will go into the description of the design with calculations performed to determine the behavior of the DC grid under rated operating conditions and *extend to fault situations.* The calculations will be used to check whether all requirements are fulfilled.

Conductor/ Wire Sizing

The electrical design must meet standard regulations. The conditions which determine the wire diameter are:

1. Highest tolerable temperature of conductors;
2. Allowable voltage drop;
3. Maximum impedance at which short circuit protection still works [1].

Voltage losses should not cause malfunction of household appliances. A footnote (NEC 210-19 FPN No. 4) states that a voltage drop of 5% at the further receptacle in a branch wiring circuit is acceptable for normal efficiency. Special attention must be paid to the insulation of the conductors to prevent arcs and corrosion. The number of conductors in a low-voltage system will increase as the main bus voltage decreases due to the increase in current.

The layout of the DC House will be based on a radial grid. Radial systems are easier to maintain and build. The protection of a radial system compared to a mesh or ring is less complex. Also, there is no significant wire reduction when using ring or mesh systems. Figure 4-1 illustrates the voltage losses for a certain wire cross-section as a function of the product of current and cable length [1].It is clear that losses are larger for a 24V system than a 78V system. This creates a limitation on our system's efficiency.

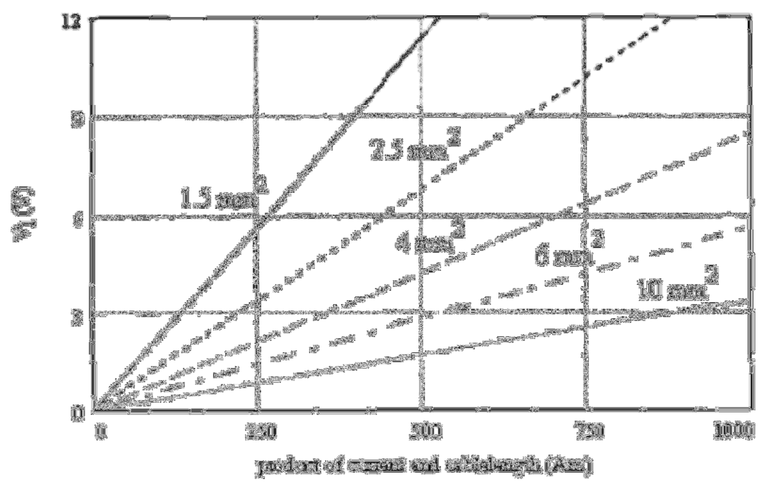


Figure 4-1: DC Voltage losses in relation to the product of current and cable length

Table 4-1: AWG Characteristics

AWG gauge	Diameter mm	Ohms per 1000 ft	Ohms per km	Max amps power transmission
3	5.82676	0.197	0.64616	75
4	5.18922	0.2485	0.81508	60
5	4.62026	0.3133	1.027624	47
6	4.1148	0.3951	1.295928	37
7	3.66522	0.4982	1.634096	30
8	3.2639	0.6282	2.060496	24
9	2.90576	0.7921	2.598088	19
10	2.58826	0.9989	3.276392	15
11	2.30378	1.26	4.1328	12
12	2.05232	1.588	5.20864	9.3
13	1.8288	2.003	6.56984	7.4
14	1.62814	2.525	8.282	5.9

The AWG information will be used in choosing the wire desired for maximum efficiency. Although, larger cables may increase cost, they are beneficial to support large loads. Large load may have large inrush currents at start. Using cables too small will limit the current available to the load preventing it from operating properly. Another perspective on cable sizing is seen from the NEN 1010 (Dutch regulations on electrical installations) illustrated in Table 4-2 where only the 24V system is given, as a reference to the design of the DC House [1]. The maximum current load is limited by the maximum tolerable conductor temperature of 70◦C. The maximum length is calculated according to a maximum voltage loss of 5% (NEC Safety Regulation).

Table 3-2: 24V System maximum current, power load and wire length

Cross-section (mm^2)	Maximum current (A)	Max. Power (W)	Max Length (m)
1.5	14	336	3.8
2.5	19.2	460.8	4.6
4	25.6	614.4	5.5
6	32.8	787.2	6.5
10	45.6	1094.4	7.7
25	80.8	1939.2	10.9
50	120.8	2899.2	14.6

In a typical house wire can easily reach lengths of 30m (131ft.). 24V systems is chosen as a reference for higher main bus voltage systems. The 24V system is a critical point since it is hard to keep voltage losses below 5% for wires longer than 30m. With a power limit of 500W, and a cross-sectional of 10 mm^2 (7 AWG) the wire cannot be longer than 17m if a maximum voltage loss of 5% is desired [1]. In summary the longer the wire required at 500W the larger the cross-sectional area needed to reduce voltage losses. The power limits and the related voltage losses result in limits for the DC Power House appliances.

Modeling of the DC System

The DC system can be divided into three parts: the source, the DC grid, and the load. Modeling of these parts will be needed to perform load flow and short circuit. Performing load flow is an essential part of predicting efficiency of the system based on different main bus voltages. After modeling the source, DC grid, and the various loads the system will be interpreted into ETAP software where a power flow will be done.

Modeling the DC Grid

Modeling of the DC grid entails choosing the layout of the loads that will result in the most efficient system. For example: radial, ring, or mesh system. The DC grid is modeled as shown in Figure 6. The resistance and inductance of the circuit depend on the length of wire, cross-section of the wires (AWG), and the layout of the system.

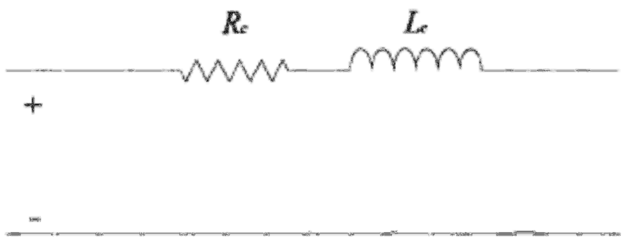


Figure 4-2: Equivalent circuit for wires

To calculate the minimum short circuit current, the resistance can be approximated by the following equation taking into account temperature change:

$$\rho(T_2) = \rho(T_1) * [1 + \propto (T_2 - T_1)] \qquad (4\text{-}1)$$

where:
p(T_2): resistance at temperature T_2;
p(T_1): resistance at initial temperature T_1;
α: 0.00323 for copper conductors;
T_1: initial temperature;
T_2: desired temperature.

For copper conductors p(20◦C) = 0.01724 Ω mm^2/m and p(70◦C) = 0.020 Ω mm^2/m.

To calculate wire inductance of the DC system, the formula of self-inductance for two parallel conductors is used:

$$L = \left[0.05 + 0.2 * \ln\frac{a}{r}\right] * 10^{-6} \qquad (4\text{-}2)$$

where:
L: self-inductance in H/m;
a: distance between conductors;
r: radius of conductors.

To consider that the conductors are not always the same distance apart L_{min} and L_{max} are approximated. The minimum distance is defined by the thickness of the insulation; where the maximum distance is determined by the diameter of the 19mm conduit assumed to be carrying the wires. Table 4-3 gives the inductance and resistance for 2.5, 4 and 6 mm^2 cross-sectional area wires.

Table 4-3: Resistance and inductance values for different wire cross-sections

A_c (mm^2)	Approx. AWG	r (mm)	a_{min} (mm)	a_{max} (mm)	R_c (Ω/m) 20°	R_c (Ω/m) 70°	Lc min (µH/m)	Lc max (µH/m)	Lc/R_{min} (ms)	Lc/R_{max} (ms)
2.5	13	0.89	3.3	15.7	0.0069	0.0080	0.31	0.62	38.8	89.9
4	11	1.13	3.9	15.1	0.0043	0.0050	0.30	0.57	60.0	132.6
6	9	1.38	4.4	14.6	0.0029	0.0033	0.28	0.52	96.6	179.3

If we assume that the wire is exactly in the middle of the copper duct, the inductance may be calculated as follows:

$$L = \left[0.2 * \ln\frac{r_2}{r_1}\right] * 10^{-6} \qquad (4\text{-}3)$$

where:
L: self-inductance in H/m;
r_1: radius of inside conductor (mm);
r_2: radius of outside conductor (mm).

Table 4-4: Resistance and inductance values for wires in copper duct

	Approx. AWG	r_1	r_2	R (Ω/m) 20°	R (Ω/m) 70°	L (µH/m)	L/R_{min} (ms)	L/R_{max} (ms)
2.5 mm^2	13	0.89	11	0.0069	0.0080	0.50	56.4	65.4
4 mm^2	11	1.13	11	0.0043	0.0050	0.46	78.4	91.1
6 mm^2	9	1.38	11	0.0029	0.0033	0.42	100.7	115.1
Copper duct 19.8x22 mm				0.00075	0.00087			

Modeling of the Loads

For load flow calculations, the household appliances are modeled as loads which draw constant current from the DC distribution network. Typical dc loads were researched and the results are summarized in Table 4-5. Table 4-6 shows the average appliance consumption taking into account the desired system efficiency.

Table 4-5: 12V and 24V Appliances for low-power consumption

Low Power Consumption Applications
(Super) efficient appliances with a maximum power demand of 400W combined: • Lightning: LEDs • DC fans • DC hot plate • Radio • Computer • Battery Charger • Refrigerator

Table 4-6: Average power consumption of DC static loads

Static Load	Avg. Power (W)	Avg. Voltage (V)	Avg. Current (V)
LED Lighting	.24W – 13W	12V, 24V	20mA – 550mA
DC fans	6W – 72W	12V, 24V	0.5A – 3A
FM Radio	2 AA Batteries	3V – 5V	-
DC Hot Plate	-	12V	-
Computer	-	19V	3.5 – 4A
Battery Charger	30W	12V	2.5A
Refrigerator	12W	12V, 24V	.5A- 1A

All loads researched have a wide range of power demands, the ones used for efficiency analysis are specific loads purposely chosen for the testing of this project. The average consumption is not limited to the research done in this project. The average in Table 4-5 is for the loads specific to this project.

V. Test Plans

Testing the efficiency of the DC Power House will be done with ETAP, Power Management System software. ETAP has the capability of modeling static loads, DC-DC converters, and wire cables. Also, ETAP is not limited to performing power flow studies, and short circuit studies. The testing of the system will be broken down into three sections: static load, DC-DC converters and wire cables. After the system is modeled appropriately, power flow studies will be made to record the efficiency of the system. Efficiency is being measured through three different methods. Efficiency will be tested with different AWG (American Wire Gauge) sizes where the wire gauge will be varied with the variation of the main bus voltage. The second method to measure efficiency of the system is by stepping, in two volt increments, from 12V to 72V at full-load and measure Pin and Pout at every increment. The third method to test efficiency is to test the common main bus voltages (12V, 24V, 48V, and 72V) and vary the percent loading on the system observing the efficiency of the system with different loading on different main bus voltages.

The efficiency of the system will vary significantly on the type of appliances used and type of DC-DC converters used. Modeling of the DC-DC converters will be done through research and finding low power, low cost, high efficiency converters. The loads modeled in ETAP come mostly from the 29th Edition 2010 Renewable Energy magazine as well as internet sources. All loads and DC-DC converters specifications are described in the "Development and Construction" section. A test of efficiency concerning the DC-DC converters will be tested by forming a system with only LED lighting where the main bus voltage will be varied at full-load.

The system layout will also be tested for efficiency. The system will be first a radial system then will be converted into a ring system to gain a more reliable system. The voltage will be varied at full-load. Another method to test the system layout efficiency is to consider the number of branches in the system. The branch efficiency test will be performed with 1, 2, 3, and 8 branches at main bus voltages 12V, 24V, 48V, and 72V exclusively.

VI. Development and Construction

Elements considered in system efficiency include DC-DC converters, wire size, wire type, and appliances. The construction of these elements will be given in detail in this section.

DC-DC Converters

DC-DC converters will be designed and modeled based on research. The manufacture used for the modeling of the DC-DC converters is Samlex America Inc. Table 6-1 detail the DC-DC converter specifications including their efficiencies based on input voltage range. A more intuitive table of the different DC-DC converters is shown in Table 6-2.

Table 6-1: DC-DC Converters Efficiencies based on output voltage

MODEL		SD-15A-05	SD-15B-05	SD-15C-05	SD-15A-12	SD-15B-12	SD-15C-12	SD-15A-24	SD-15B-24	SD-15C-24
OUTPUT	DC VOLTAGE	5V			12V			24V		
	RATED CURRENT	3A			1.25A			0.625A		
	CURRENT RANGE	0 ~ 3A			0 ~ 1.25A			0 ~ 0.625A		
	RATED POWER	15W			15W			15W		
	RIPPLE & NOISE (max.) Note.2	100mVp-p			120mVp-p			150mVp-p		
	VOLTAGE ADJ.RANGE	4.75~5.5VDC			10.8~13.2VDC			21.6~26.4VDC		
	VOLTAGE TOLERANCE Note.3	±2.0%			±1.0%			±1.0%		
	LINE REGULATION	±0.5%			±0.3%			±0.2%		
	LOAD REGULATION	±0.5%			±0.3%			±0.2%		
	SETUP, RISE ,HOLD UP TIME	2.5s, 25ms,--- 12VDC/24VDC/48VDC at full load								
INPUT	VOLTAGE RANGE	A: 9.2 ~18VDC	B:18 ~ 36VDC	C:36~72VDC						
	EFFICIENCY(Typ.)	68%	76%	75%	72%	76%	79%	70%	77%	78%
	DC CURRENT(Typ.)	1.9A/12VDC	0.9A/24VDC		0.45A/48VDC					

Table 6-2: DC-DC converters used in DC Power House

Models			
Model Number	Input Voltage	Output VDC Voltage	Output Amps
SD-15A-5	9.2 ~ 18 VDC	5 VDC	3.0
SD-15A-12	9.2 ~ 18 VDC	12 VDC	1.25A
SD-15A-24	9.2 ~ 18 VDC	24 VDC	.625 A
SD-15B-5	18 ~ 36 VDC	5 VDC	3.0 A
SD-15B-12	18 ~ 36 VDC	12 VDC	1.25 A
SD-15B-24	18 ~ 36 VDC	24 VDC	.625 A
SD-15C-5	36 ~ 72 VDC	5 VDC	3.0 A
SD-15C-12	36 ~ 72 VDC	12 VDC	1.25 A
SD-15C-24	36 ~ 72 VDC	24 VDC	.625 A

As the voltage is varied on different simulations the efficiency of the converter need to be adjusted to accurately represent the efficiency of the system. Efficiency of the system greatly depends on the DC-DC converter efficiency; this will be demonstrated in test results. For the battery charger load on the system a different DC-DC converter was used. The use of a different DC-DC converter was needed since the current drawn exceeded the SD-15 models.

Appliances (Static Loads)

The various loads used in the ETAP simulation are from the “29th Edition 2010 Renewable Energy Design Guide & Catalog”, reference [3].

DC Refrigerator

Low power DC refrigerator loads are hard to find and costly. SunDanzer has a section on super-efficient refrigerators and freezers; a selection is shown in Table 6-3 taken from the catalog.

Table 6-3: SunDanzer brand super-efficient refrigerator and freezer

Model	12/24 VDC models	Ah/day @ 12V			Outside dimensions H" x W" x D"	Weight (lbs)	Item code	Price
		at 70ºF	at 90ºF	110ºF				
DCR50	50L (1.8 cu ft.) refrigerator	4.6	9.4	20	26.5 x 30.5 x 23	75	080-02115	$699
DCR165	165L (5.8 cu ft.) refrigerator	6.5	14	29	34.5 x 36.8 x 26.2	120	080-02119	$1,149
DCR225	225L (8 cu ft.) refrigerator	7.5	17	33	34.5 x 46.9 x 26.2	140	080-02123	$1,249
DCF50	50L (1.8 cu ft.) freezer	15	24.5	42	26.5 x 30.5 x 23	75	080-02114	$699
DCF165	165L (5.8 cu ft.) freezer	23	37	64	34.5 x 36.8 x 26.2	120	080-02117	$1,149
DCF225	225L (8 cu ft.) freezer	30	44	68	34.5 x 46.9 x 26.2	140	080-02121	$1,249

DC Fan

DC Fan selection was based on rpm and wattage. The first fan was selected from the catalog where the second fan was selected based on performance. Nextek's vari-fan draws 0.5 amps at 12 VDC and 0.78 amps at 24 VDC. At 12 VDC the 5-blade fan will have approximately 60 rpm moving 1,500 CFM when mounted at least 8 feet above the floor in an open room. At 24 VDC the 5-blade fan will have approximately 120 rpm moving 2,700 CFM when mounted at least 8 feet above the floor in an open room [3]. In ETAP simulation the fan is modeled as a motor operating at 85% efficient, allowing the fan to draw 21W instead of the typical 18W.

Wire/Cable Type

The selection of wire cable type is based on NEC requirements. Wire sizes including cost per foot are taken from [3]. The wire selected is a 2-conductor flexible wire UL listed stranded type THHN/THWN AWG No. 10. Figure 6-2 and 6-3 display the wire selection in ETAP. The impedance of the wire matches the theoretical design impedance. Figure 6-1 gives a more detailed description of wire type chosen and the cost associated with choosing AWG No. 10.

WIRE & CABLE

Tray Cable (TC)

This 2-conductor flexible wire is excellent for outdoor applications like PV array lead-in and subarray wiring. It may be buried directly in the ground or exposed to direct sunlight. 10- and 12-gauge are good for array interconnects. UL Listed, stranded type THHN/THWN conductors. Conductor insulation is red and black.

Description	Item code	Price/foot
8 AWG 2-conductor TC cable	050-01156	$2.16
10 AWG 2-conductor TC cable	050-01162	$1.69
12 AWG 2-conductor TC cable	050-01174	$0.94
16 AWG 2-conductor TC cable	050-01177	$0.46
18 AWG 2-conductor TC cable	050-01180	$0.35

Figure 6-1: Wire Cable THHN/THWN 2 conductor

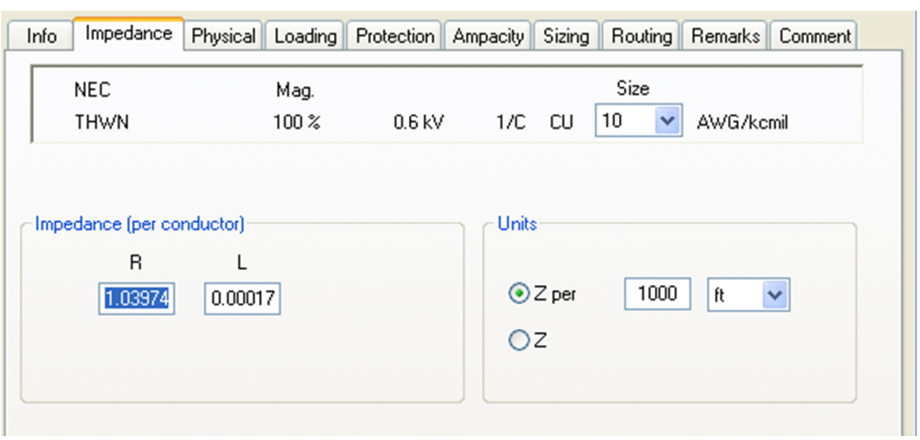


Figure 6-2: NEC wire resistance for a THWN AWG No. 10 rated up to 600V

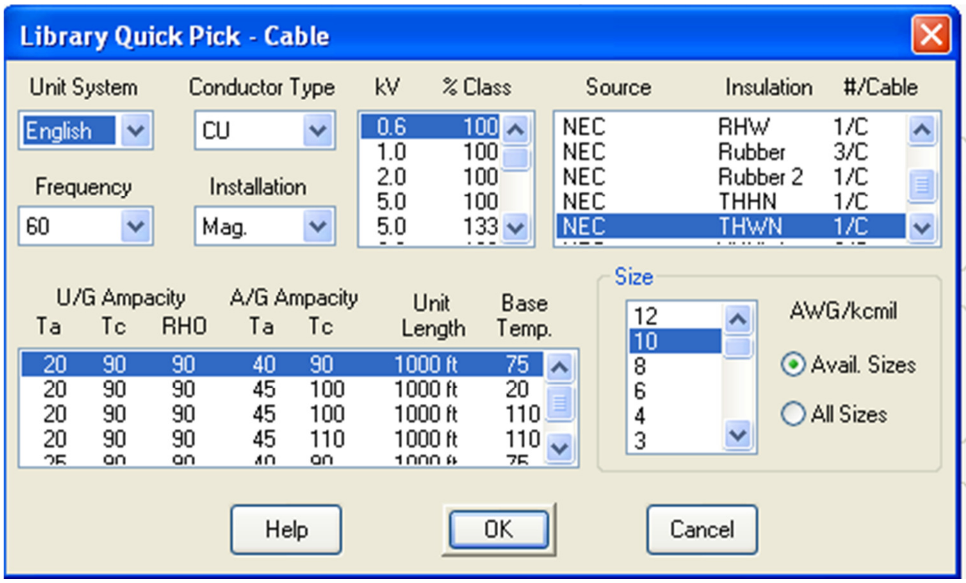


Figure 6-3: NEC wire specifications for a THWN AWG No. 10 rated up to 600V

VII. Integration and Test Results

AWG Efficiency

Testing of the AWG efficiency is the first step in determining the most efficient main bus voltage. AWG determines the copper loss in the wire. The smaller the AWG the larger the cross-sectional area of wire increasing its wire resistance. The highest wire resistance will result in the highest voltage drop by the equation $P = I^2R$. The draw back with choosing the largest wire comes with an increase in cost per foot. Tables 7-1 through 7-4 are the result of different AWG values in a main bus voltage system. The system for each wire gauge was tested at full load where the main bus voltage efficiency stayed constant. It can be concluded that as the AWG No. increases the main bus voltage drop increases, reducing the overall system efficiency.

Table 7-1: 12V System Varying AWG at full-load

12V Main Bus System					
AWG No.	Pin (W)	Pout (W)	η Efficiency (%)	P_{Loss} (W)	Main Bus Cable Voltage Drop (%)
4	372	254	68.28	118	1.5
6	375	254	67.73	121	2.5
8	391	234	59.85	157	-
10	381	254	66.67	127	4
12	410	254	61.95	156	10.9

Table 7-2: 24V System Varying AWG at full-load

24V Main Bus System					
AWG No.	Pin (W)	Pout (W)	η Efficiency (%)	P_{Loss} (W)	Main Bus Cable Voltage Drop (%)
4	333	254	76.28	79	0.3
6	334	254	76.05	80	0.5
8	337	254	75.37	83	-
10	335	254	75.82	81	0.9
12	340	254	74.71	86	2.2

Table 7-4: 48V System Varying AWG at full-load

48V Main Bus System					
AWG No.	Pin (W)	Pout (W)	η Efficiency (%)	P_{Loss} (W)	Main Bus Cable Voltage Drop (%)
4	326	254	77.91	72	0.1
6	327	254	77.68	73	0.1
8	327	254	77.68	73	-
10	327	254	77.68	73	0.2
12	328	254	77.44	74	0.6

Table 7-5: 72V System Varying AWG at full-load

72V Main Bus System					
AWG No.	Pin (W)	Pout (W)	η Efficiency (%)	P_{Loss} (W)	Main Bus Cable Voltage Drop (%)
4	326	254	77.91	72	0
6	326	254	77.91	72	0.1
8	326	254	77.91	72	-
10	326	254	77.91	72	0.1
12	327	254	77.68	73	0.2

Figure 7-1 shows the relationship between main bus voltage efficiency and AWG. AWG No. 10 was chosen for the rest of the analysis since it is in the middle. Choosing the most efficient wire will be the most costly, and choosing the smallest wire will bring the most lost.

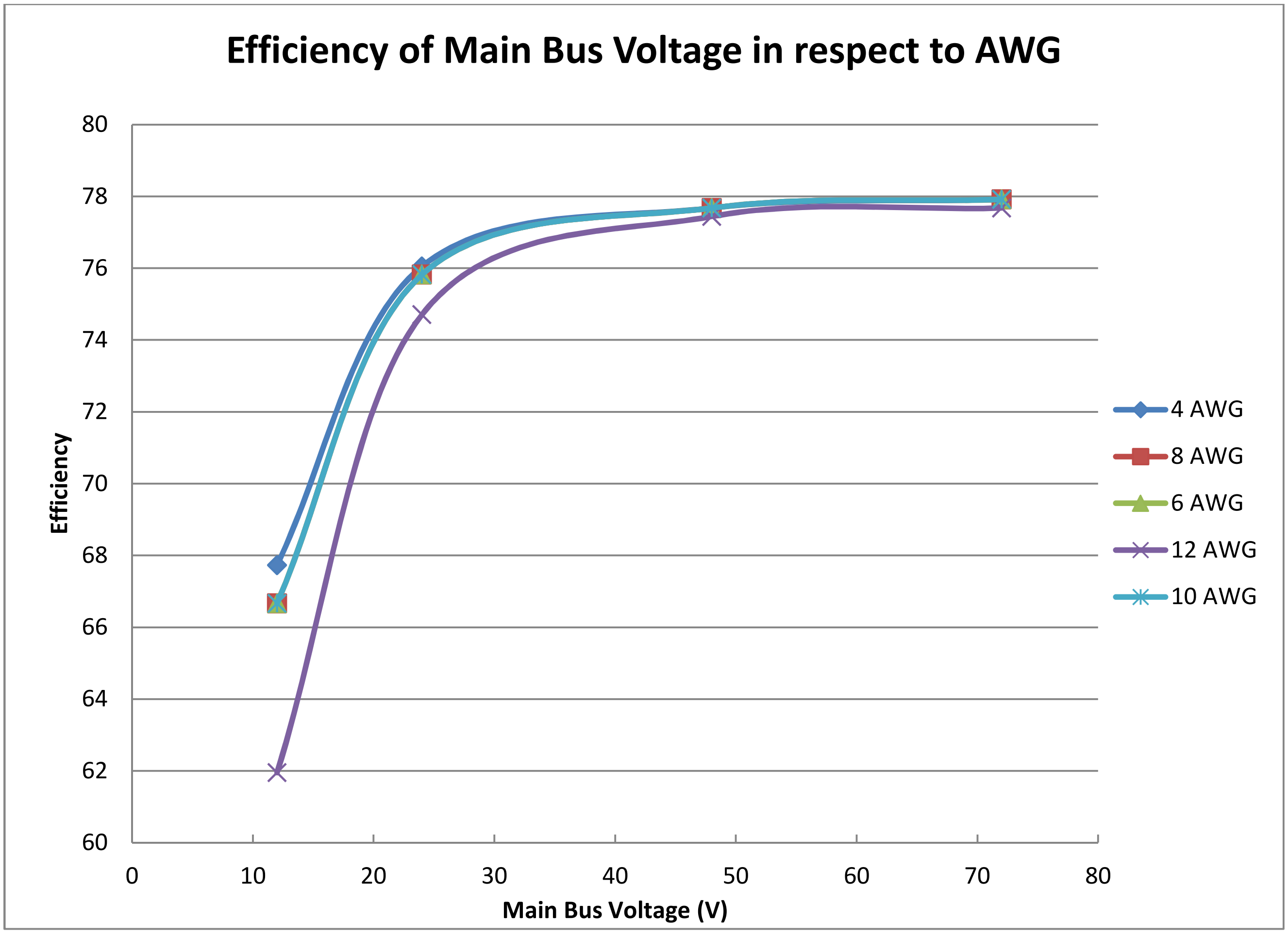


Figure 7-1: Efficiency of Main Bus Voltage in respect to AWG

Main Bus Voltage Efficiency

The main bus voltage efficiency is determined by varying the main bust voltage while being at full-load. The result is shown in Figure 7-2. The discontinuities in the data points are due to the different DC-DC converter efficiencies. The DC-DC converter efficiency varies with the range of input voltage. A line of best fit is done to approximately represent the result, and to visually represent the trend in efficiency as main bus voltage is increased. It can be concluded that the highest overall system efficiency lies at the highest main bus voltage. It can be shown that as the main bus voltage is increased the current is decreased, reducing copper losses in the wire therefore increasing efficiency. Choosing the main bus voltage cannot be determined just from looking at the graph in Figure 7-2, there are other factors that affect overall system efficiency which will be obtained from other efficiency tests.

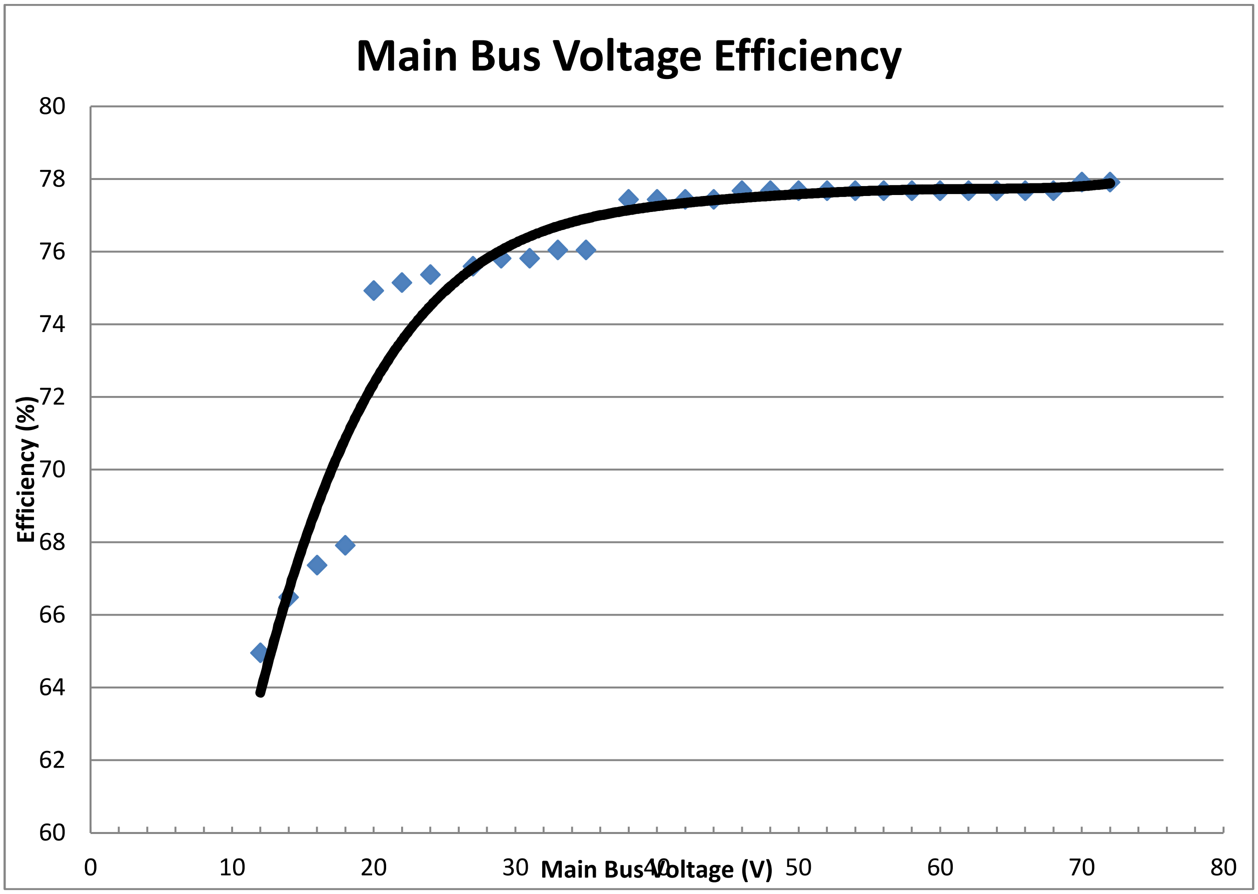


Figure 7-2: Variable Bus Voltage at 100% Load (No. 10 AWG, 3 branches)

Percent Loading Efficiency

Variation in load is very common. Systems typically are not always powered at full-load instead less. A load variation efficiency test is very crucial when determining which main bust voltage is the most efficient. Figure 73 displays the result of varying percent loading while keeping the main bus voltage constant. It is concluded, that by keeping the main bus voltage at 48V and varying the percent loading the overall system efficiency is greatest. Figure 7-3 also shows an increase in overall system efficiency when the percent loading is low. This is due to the fact that at low percent loading, only LED lighting is consuming power. LED lighting has very high power efficiency. Throughout the system the DC fans run the max 85% efficient lowering the overall system efficiency.

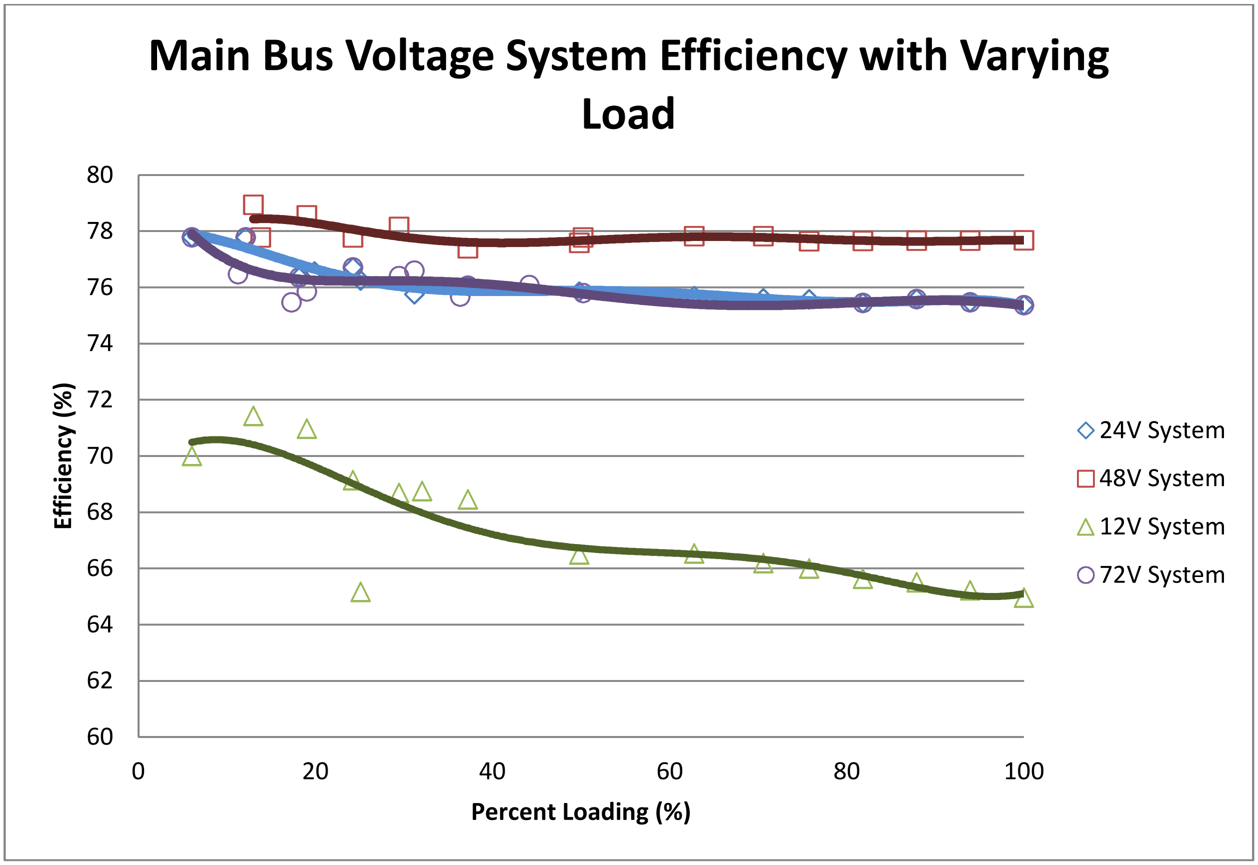


Figure 7-3: Main Bus Voltage System Efficiency with Varying Load (AWG No. 10)

LED Load Efficiency

DC-DC converter efficiency plays a major role in overall system efficiency. Pure DC-DC converter efficiency is tested using a 100W pure LED lighting system shown Appendix A. Table 7-7 shows the efficiency results when the main bus voltage is changed in two volt increment with full-load power consumption. As it may be observed the overall system efficiency is in the range of the DC-DC converter efficiency; the overall efficiency is stable within the range of the main bus voltage. It is concluded that as DC-DC converter efficiency increases, the overall system efficiency increases. Table 7-6 also demonstrates the conclusion of DC-DC converter efficiency by demonstrating that as the percent load of the system changes, the overall system efficiency is the DC-DC converter efficiency.

Table 7-6: 48V Main Bus LED Lights efficiency varying percent load

%Load	Pin (W)	Pout (W)	n(efficiency) (%)
100.00	126	98	77.78
85.71	108	84	77.78
71.43	90	70	77.78
57.14	72	56	77.78
42.86	54	42	77.78
28.57	36	28	77.78
14.29	18	14	77.78

Table 7-7: LED light load efficiency with varying main bus voltage running 100% Load

DC-DC Converter Efficiency (%)*	Voltage (V)	Pin (W)	Pout (W)	ɳ(efficiency) (%)
78-79%	72	126	98	77.78
	60	126	98	77.78
	58	126	98	77.78
	56	126	98	77.78
	54	126	98	77.78
	52	126	98	77.78
	50	126	98	77.78
	48	126	98	77.78
	46	126	98	77.78
	44	126	98	77.78
	42	126	98	77.78
	38	126	98	77.78
76-77%	36	128	98	76.56
	34	128	98	76.56
	32	128	98	76.56
	30	128	98	76.56
	28	128	98	76.56
	26	128	98	76.56
	24	128	98	76.56
	22	128	98	76.56
	20	128	98	76.56
70-72%	18	142	98	69.01
	16	142	98	69.01
	14	143	98	68.53
	12	144	98	68.06

*Efficiency range depends on output voltage of converter. Efficiency equals 79% for output voltage of 24V when Vin is in the range for 36V-72V.

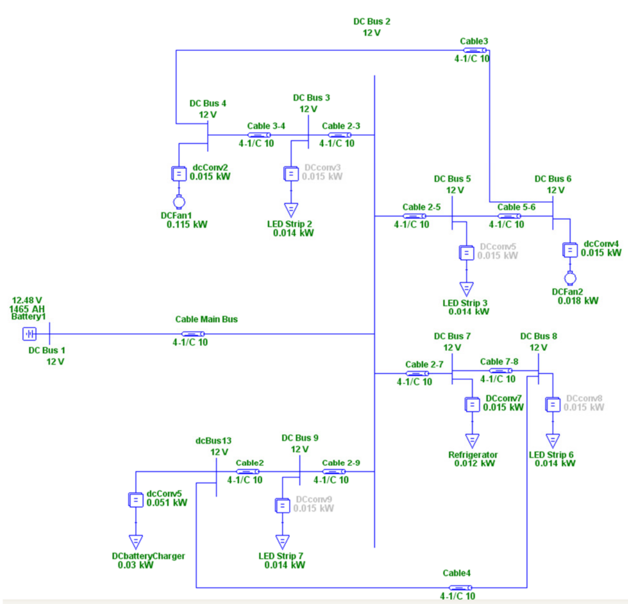
System Layout Efficiency

The four main distribution system configurations are: radial, loop (ring), network and primary selective. For the DC Power House the radial, ring, and network configurations will be tested.

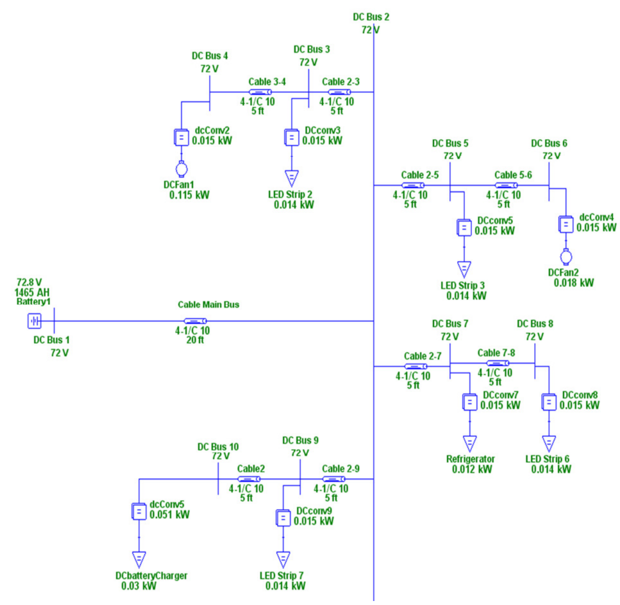
Radial vs. Ring Distribution

In a radial distribution system the feeders branch out to several distribution centers without intermediate connections between feeders allowing only one direct path to a load [4].The radial system is most widely used for its simplicity and least expensive to build as well as simple expansion procedures. The downfall of a radial system is the lack of reliability. The fault or loss of a transmission loss will result in the loss of all the loads attached to that feeder. For example, if there is a fault at DC Bus 3, in Figure 7-4, DC Fan 1 will have no power distributed to it since its only path for power was through DC Bus 3.

In a loop configuration there are intermediate connections between feeders allowing for multiple paths to a load. It is more expensive to build than radial type, but is it more reliable. In case of a fault, the power is supplied to the load through another path. Also, it is more convenient to do maintenance in the system when a ring system is used. The loop system enables the use of a smaller wire, assuming that the current does split evenly between the two wires.



4 Branch Ring Distribution System



4 Branch Radial Distribution System

Figure 7-4: Ring System (LEFT) compared to Radial System (RIGHT)

Table 7-8: Comparison between Pin in radial and ring systems

12V Main Bus System 3 Branches		
% Load	Pin (Radial)	Pin (Ring)
100.00	391	390
93.94	368	367
87.88	345	344
81.82	323	321
75.76	300	299
70.56	281	280
62.77	248	247
49.78	203	202
37.23	130	130
32.03	112	112
29.44	99	99
25.11	89	89
24.24	81	81
19.05	62	62
12.99	42	42
6.06	20	20

As seen in Table 7-8, power efficiency remains the same for a radial and loop system. Although loop system is more reliable the efficiency is not greatly dependent on the system configuration. The configuration does dramatically affect the cost of the system since wire size will be minimized with a loop system. Loop system currents are less than the radial system currents due to different paths available for power flow dramatically reducing losses in the wires.

Number of Branches

An increase in number of branches not only increases reliability but also decreases the amount of current flown within each branch. Appendix A shows the DC Power House system as a two branch system, four branch system and eight branch system. Power flow currents demonstrate a decrease in current through the wire as the number of branches increases. Table 7-9 proves that as the number of branches increases the efficiency of the system increases. The most efficient system is shown to be 72V with an efficiency of 77.91%. The reason 72V seems to be the most efficient system is due to the low currents; higher voltage leads to lower currents leading to less copper power losses.

Table 7-9: Different branch system efficiencies

# Branch System Efficiencies					
Main Bus Voltage (V)	**n_{1B} (%)**	**n_{2B} (%)**	**n_{3B} (%)**	**n_{4B} (%)**	**n_{8B} (%)**
12	59.48	63.66	59.85	64.96	65.46
24	74.27	75.15	75.37	75.37	75.60
48	77.44	77.44	77.68	77.68	77.68
72	77.68	77.68	77.91	77.91	77.91

Conclusion

In order to determine the main bus system voltage that would generate the highest system efficiency when accounting for: wire size, different loads, maximum of 500 W power input, and different distribution system implementation (mesh or radial) requires a number of different efficiency tests to be analyzed. Test include: AWG efficiency, main bus voltage efficiency, DC-DC converter efficiency using LED loads only, and system layout efficiency. An individual conclusion can be drawn from each test, but an overall conclusion can only be drawn by incorporating all the results.

It is concluded that AWG No. 10 and bigger will give the highest efficiency power transfer. Choosing AWG No. 10 will reduce cost, and will provide adequate power distribution throughout the system. The main bus voltage efficiency test shows an increase in system efficiency with an increase in main bus voltage. Although, the highest efficiency is gained at 72V at full-load, this alone does not determine the most efficient main bus voltage; other considerations must be taken into account. For example variation in loading efficiency is a major contribution to selecting the most efficient main bus voltage. The 48V system appeared to be the most efficient system when the percent loading was varied.

The overall system efficiency can be predicted ahead of time by the choosing of the DC-DC converters. An LED load only test was done to prove that the overall system efficiency resembled the DC-DC converter efficiency. System layout also plays a major role in system efficiency as well as in reliability. As the number of branches increases the system efficiency also increases. Another advantage with an increase in branches is to be able to reduce wire size due to the decrease in current the DC House overall efficiency in this design did not exceed 80%.

Implementing a radial system, although easier to implement DC fault protection, is not as reliable as the ring system.

Recommendation

To further test these conclusion a network configuration of the DC House must be implemented. Also, the DC-DC converter efficiencies at partial loading must be research more in depth. Different load efficiencies should be taken into consideration. DC distribution protection should be based on power flow currents and both radial and ring systems need to be considered. Wire size should be analyzed in terms of percentage loss throughout system, and different wire types should be

Bibliography

[1] J. Pellis. 1998. The DC low-voltage house. Research by ECN (Energy Centre The Netherlands), Petten.

[2] Engelen, K.; Leung Shun, E.; Vermeyen, P.; Pardon, I.; D'hulst, R.; Driesen, J.; Belmans, R.; , "The Feasibility of Small-Scale Residential DC Distribution Systems," *IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on* , vol., no., pp.2618-2623, 6-10 Nov. 2006
doi: 10.1109/IECON.2006.347246
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4153073&isnumber=4152825

[3] AEE Solar. *29th Edition 2010 Renewable Energy Design Guide and Catalog* 2010: 1-208. Print.

Appendices A – System Layouts

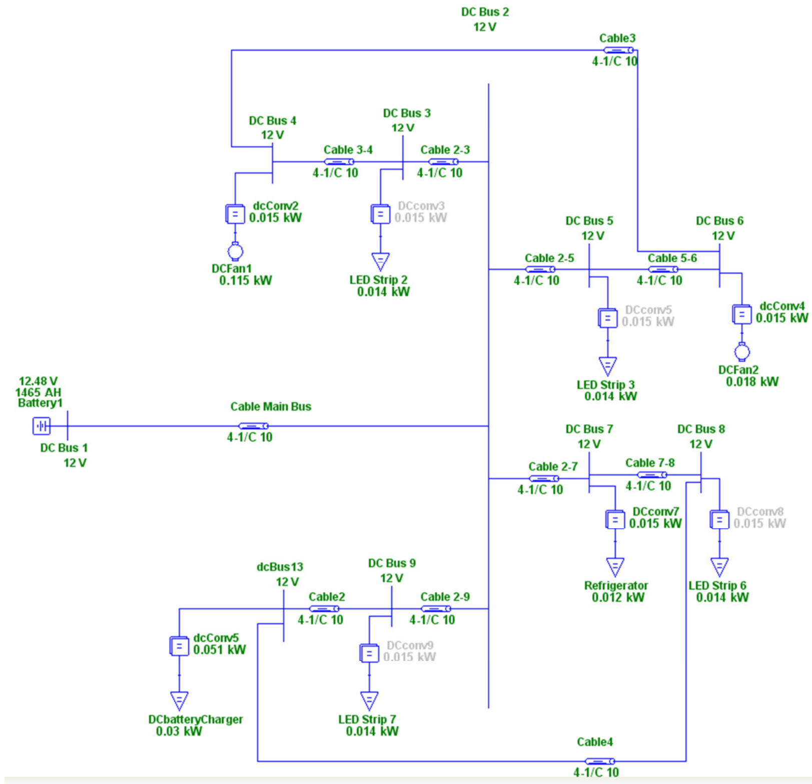


Figure A-1: 12V Ring System, 3 branch under load test

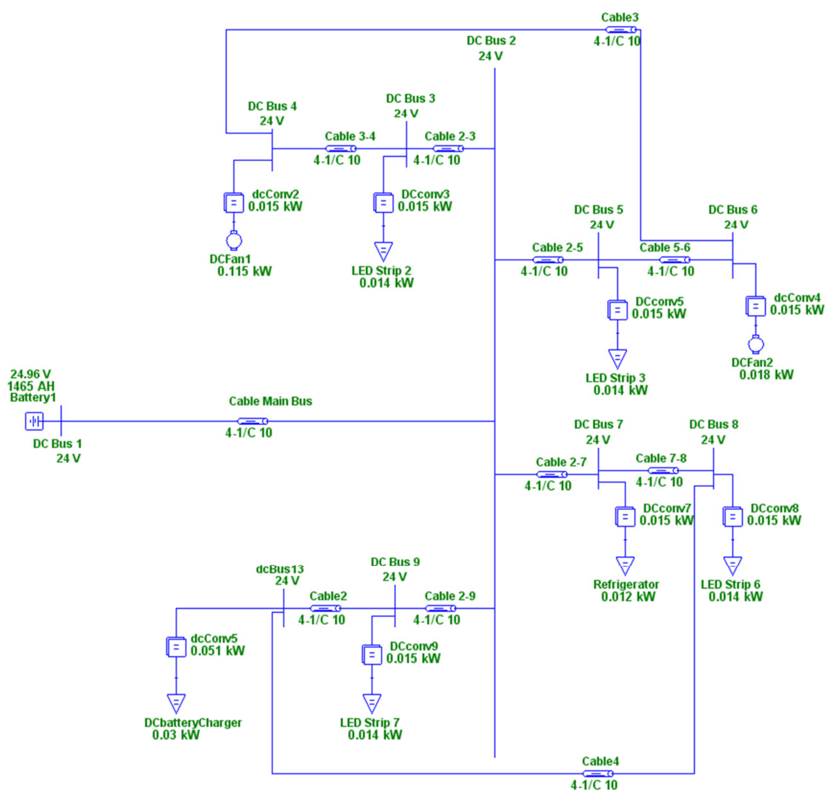


Figure A-2: 24V Ring System, 3 Branch

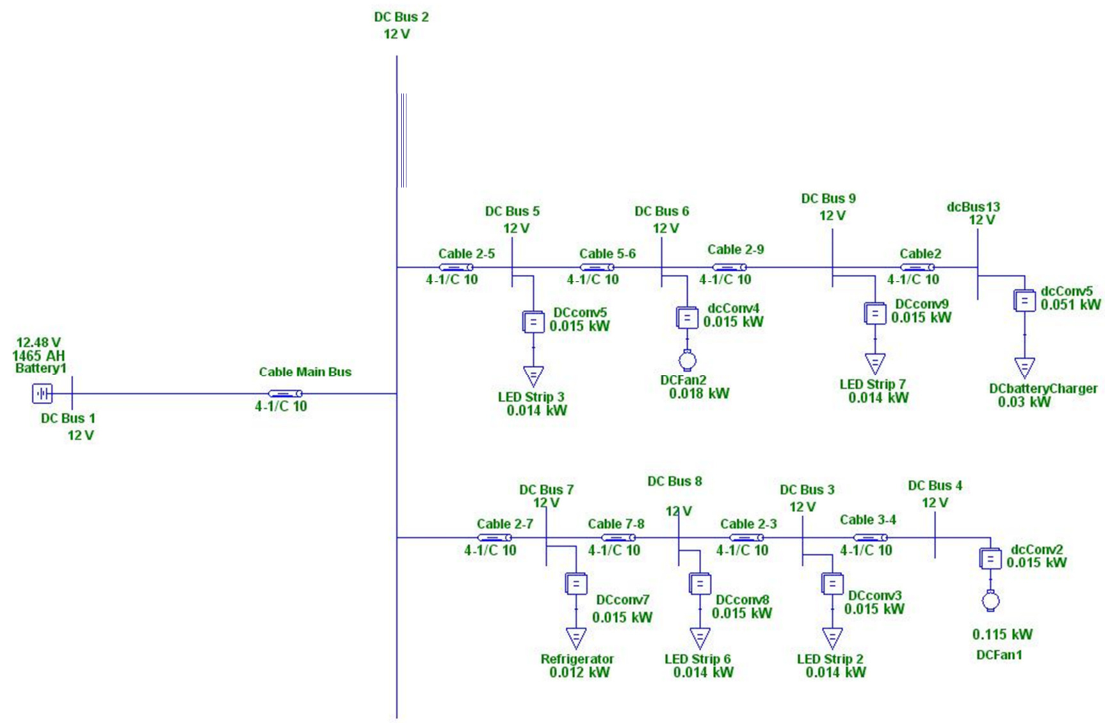


Figure A-3: 12V 2 Branch System

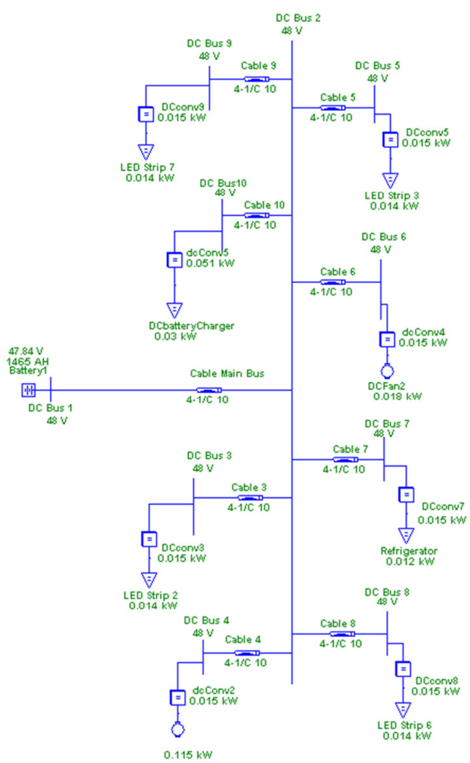


Figure A-4: 8 Branch System

Appendix B – Raw Data

Table B-1: Raw Data

System Bus Volt	Pin (W)	Pin (W)	Pin (W)	Pin (W)	Pin (W)	Pout	n (%)	n (%)	n	n	n	% Volt. Drop	% Volt. Drop	% Volt. Drop	% Volt. Drop	% Volt. Drop
12	427	399	-	391	388	254	59.48	63.66	-	64.96	65.46	7.1	6.6	-	-	6.4
14	-	387	-	382	-	254	-	65.63	-	66.49	-	-	-	-	-	-
16	-	381	-	377	-	254	-	66.67	-	67.37	-	-	-	-	-	-
18	-	377	-	374	-	254	-	67.37	-	67.91	-	-	-	-	-	-
20	-	341	-	339	-	254	-	74.49	-	74.93	-	-	-	-	-	-
22	-	339	-	338	-	254	-	74.93	-	75.15	-	-	-	-	-	-
24	342	338	-	337	336	254	74.27	75.15	-	75.37	75.60	1.4	1.4	-	-	1.4
27	-	337	-	336	-	254	-	75.37	-	75.60	-	-	-	-	-	-
29	-	336	-	335	-	254	-	75.60	-	75.82	-	-	-	-	-	-
31	-	336	-	335	-	254	-	75.60	-	75.82	-	-	-	-	-	-
33	-	335	-	334	-	254	-	75.82	-	76.05	-	-	-	-	-	-
35	-	335	-	334	-	254	-	75.82	-	76.05	-	-	-	-	-	-
38	-	329	-	328	-	254	-	77.20	-	77.44	-	-	-	-	-	-
40	-	328	-	328	-	254	-	77.44	-	77.44	-	-	-	-	-	-
42	-	328	-	328	-	254	-	77.44	-	77.44	-	-	-	-	-	-
44	-	328	-	328	-	254	-	77.44	-	77.44	-	-	-	-	-	-
46	-	328	-	327	-	254	-	77.44	-	77.68	-	-	-	-	-	-
48	328	328	327	327	327	254	77.44	77.44	77.68	77.68	77.68	0.4	0.4	-	-	0.4
50	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
52	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
54	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
56	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
58	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
60	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
62	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
64	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
66	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
68	-	327	-	327	-	254	-	77.68	-	77.68	-	-	-	-	-	-
70	-	327	-	326	-	254	-	77.68	-	77.91	-	-	-	-	-	-
72	327	327	-	326	326	254	77.68	77.68	-	77.91	77.91	0.2	0.2	-	-	0.2

1 Branch   2 Branch   3 Branch   4 Branch   8 Branch

-values not filled in were not evaluated for the purpose of only main bus voltages only needed to be evaluated.

Table B-2: 24V System Varying Load 4 Branch Raw Data

24V System Varying Load 4 Branch No.10 AWG

% Load	Pin	Pin (4 branch Ring)	Pout	Pout	n (efficiency)	n (efficiency)	Pin - Pout
100	337	337	254	254	75.37091988	75.37091988	83
93.94	318	318	240	240	75.47169811	75.47169811	78
87.88	299	300	226	226	75.58528428	75.33333333	73
81.82	281	281	212	212	75.44483986	75.44483986	69
75.76	262	262	198	198	75.57251908	75.57251908	64
70.56	246	246	186	186	75.6097561	75.6097561	60
62.77	218	217	165	165	75.68807339	76.03686636	53
50.22	178	177	135	135	75.84269663	76.27118644	43
49.78	117	117	89	89	76.06837607	76.06837607	28
37.23	99	99	75	75	75.75757576	75.75757576	24
29.44	80	80	61	61	76.25	76.25	19
24.24	73	73	56	56	76.71232877	76.71232877	17
19.05	64	64	49	49	76.5625	76.5625	15
13.85	55	55	42	42	76.36363636	76.36363636	13
12.99	36	36	28	28	77.77777778	77.77777778	8
6.06	18	18	14	15	77.77777778	83.33333333	4

Table B-3: 12V System Varying Load Raw Data

12V System Varying Load 4 Branch No.10 AWG

% Load	Pin	Pin (4 branch Ring)	Pout	n (efficiency)	n (efficiency)	Pin - Pout
100	391	337	254	64.96163683	65.12820513	137
93.94	368	367	240	65.2173913	65.39509537	128
87.88	345	344	226	65.50724638	65.69767442	119
81.82	323	321	212	65.63467492	66.04361371	111
75.76	300	299	198	66	66.22073579	102
70.56	281	280	186	66.19217082	66.42857143	95
62.77	248	247	165	66.53225806	66.80161943	83
50.22	203	202	135	66.50246305	66.83168317	68
49.78	130	130	89	68.46153846	68.46153846	41
37.23	112	112	77	68.75	68.75	35
29.44	99	99	68	68.68686869	68.68686869	31
24.24	89	89	58	65.16853933	65.16853933	31
19.05	81	81	56	69.13580247	69.13580247	25
13.85	62	62	44	70.96774194	70.96774194	18
12.99	42	42	30	71.42857143	71.42857143	12
6.06	20	20	14	70	70	6

Table B-4: 48V System Varying Load Raw Data

48V System Varying Load 4 Branch No.10 AWG

% Load	Pin	Pin (4 branch Ring)	Pout	n (efficiency)	n (efficiency)	Pin - Pout
100	327	327	254	77.67584098	77.67584098	73
93.94	309	309	240	77.66990291	77.66990291	69
87.88	291	291	226	77.66323024	77.66323024	65
81.82	273	273	212	77.65567766	77.65567766	61
75.76	255	255	198	77.64705882	77.64705882	57
70.56	239	239	186	77.82426778	77.82426778	53
62.77	212	212	165	77.83018868	77.83018868	47
50.22	153	153	119	77.77777778	77.77777778	34
49.78	174	174	135	77.5862069	77.5862069	39
37.23	115	115	89	77.39130435	77.39130435	26
29.44	87	87	68	78.16091954	78.16091954	19
24.24	72	72	56	77.77777778	77.77777778	16
19.05	56	56	44	78.57142857	78.57142857	12
13.85	45	45	35	77.77777778	77.77777778	10
12.99	38	38	30	78.94736842	78.94736842	8
6.06	18	18	14	77.77777778	77.77777778	4

Table B-5: 72V System Varying Load Raw Data

72V System Varying Load 4 Branch No.10 AWG

% Load	Pin	Pin (4 branch Ring)	Pout	n (efficiency)	n (efficiency)	Pin - Pout
100	337	337	254	75.37091988	22.36525813	83
93.94	318	318	240	75.47169811	23.7332384	78
87.88	299	299	226	75.58528428	25.27935929	73
81.82	281	281	212	75.44483986	26.84869746	69
75.76	157	157	119	75.79617834	48.2778206	38
70.56	138	138	105	76.08695652	55.13547574	33
62.77	117	117	89	76.06837607	65.01570604	28
50.22	111	111	84	75.67567568	68.17628439	27
49.78	92	92	72	78.26086957	85.06616257	20
37.23	94	94	72	76.59574468	81.48483477	22
29.44	89	89	68	76.40449438	85.8477465	21
24.24	73	73	56	76.71232877	105.0853819	17
19.05	58	58	44	75.86206897	130.7966706	14
13.85	55	55	42	76.36363636	138.8429752	13
12.99	53	53	40	75.47169811	142.3994304	13
6.06	36	36	28	77.77777778	216.0493827	8

$$\% \, Load = \frac{Full\ Load\ (W) - Watts\ Removed}{Full\ Load\ (Watts)} * 100 \qquad \eta\ (Efficiency) = \frac{P_{in}}{P_{out}} * 100$$

Table B-6: Variable Bus System at 100% Full-Load Raw Data

Variable Bus System at 100% Full-load (No. 10 AWG)

System Bus Volt	Pin	Pout	n (efficiency)	Pin - Pout (Ploss Watts)
12	391	254	64.96163683	137
14	382	254	66.4921466	128
16	377	254	67.37400531	123
18	374	254	67.9144385	120
20	339	254	74.92625369	85
22	338	254	75.14792899	84
24	337	254	75.37091988	83
27	336	254	75.5952381	82
29	335	254	75.82089552	81
31	335	254	75.82089552	81
33	334	254	76.04790419	80
35	334	254	76.04790419	80
38	328	254	77.43902439	74
40	328	254	77.43902439	74
42	328	254	77.43902439	74
44	328	254	77.43902439	74
46	327	254	77.67584098	73
48	327	254	77.67584098	73
50	327	254	77.67584098	73
52	327	254	77.67584098	73
54	327	254	77.67584098	73
56	327	254	77.67584098	73
58	327	254	77.67584098	73
60	327	254	77.67584098	73
62	327	254	77.67584098	73
64	327	254	77.67584098	73
66	327	254	77.67584098	73
68	327	254	77.67584098	73
70	326	254	77.91411043	72
72	326	254	77.91411043	72